Adaptive noise subtraction for measurement of evoked field with various models and adaptation parameters

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1 Introduction

Noise subtraction using reference channel data has been used to improve signal-to-noise ratio in magnetoencephalography. For the noise subtraction, various models on the noise and signal are used. Noise in the MEG signal may have two components: one is correlated external noise which acts coherently to all the signal channels, and the other is random noise due to electronics noise or antenna noise which is incoherent each other. The correlated noise may be measurable by reference channels, and then, can be subtracted from the signal channels. Depending on the subtraction strategy, adaptive or non-adaptive method is used.

In this paper, various noise subtraction models and parameters are analyzed. For this purpose a home-built 40 channel MEG system is used for measuring evoked field with auditory stimuli. In the following the developed 40 channel MEG system is briefly described. Models considered in the noise subtraction are described, and performances of the models and parameters are given. Finally measured evoked field with the optimized noise subtraction model is shown by the developed 40 channel MEG system. Two-dimensional topographic map is also shown with cubic spline interpolation.

2 Methods

2.1 The 40 Channel MEG system

A low-noise 40-channel superconducting quantum interference device (SQUID) system was developed for measuring neuromagnetic fields [1]. The main features of the system are use of a double relaxation oscillation SQUID (DROS), a second generation SQUID, and a planar gradiometer for measuring magnetic field components tangential to the head surface. The DROSs with high flux-to-voltage transfers enabled direct readout of the SQUID output by room-temperature electronics, and simple flux-locked loop circuits could be used for SQUID operation. The pickup coil is an integrated first-order planar gradiometer with a baseline of 40 mm. The average noise level of the 40 channels is around 1.2 fT/cm/$\sqrt{}$Hz at 100 Hz, corresponding to a field noise of 5 fT/$\sqrt{}$Hz at 100 Hz, operated inside a magnetically shielded room. Four reference channels are additionally added for measuring external noise for the noise subtraction. The arrangement of the SQUID sensors (40 signal channels and 4 reference channels) is shown in Fig.1. The system has planar surface covering about 10cm x 10cm capable of regional head and cardiac imaging.

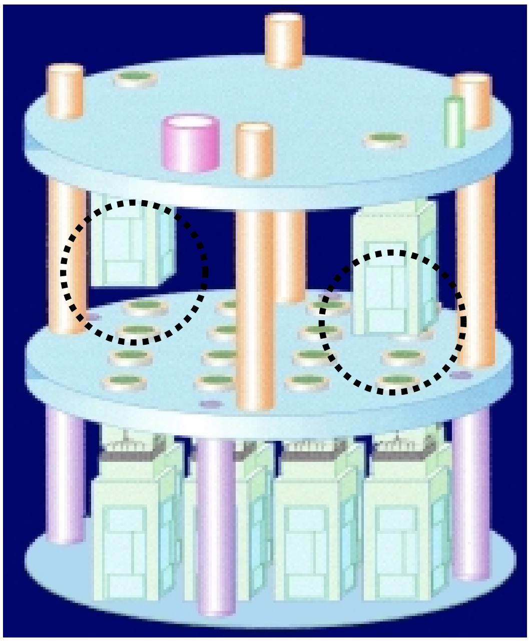


Figure 1: *Structure of the insert and arrangement of SQUID sensors. Four noise channels are arranged in the upper part marked with circles, and 40 signal channels are shown in the lower part to measure near neuromagnetic filed. Subject is located at the bottom of the structure.*

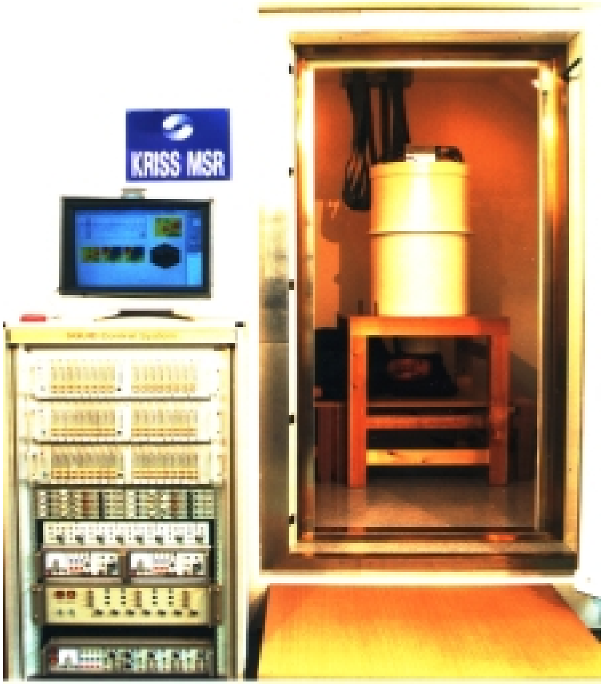


Figure 2: *Photograph of the developed 40 channel SQUID system for measuring neuromagnetic field.*

The SQUID insert was designed to have low thermal load, minimizing the loss of liquid helium. The signal processing software provides digital filtering, spectral analysis and iso-field mapping. The 40-channel system was applied to measure auditory-evoked neuromagnetic fields. A photograph of the developed 40 channel system is shown in Fig.2.

2.2 Noise subtraction models

Noise in the MEG signal may be composed of two parts: one is external noise coherent to all the signal channels and the other is uncorrelated random noise due to electronic amplifiers and filters and antenna. The former noise may be subtracted from the signal channel if the external noise is properly estimated. For the estimation of external noise, measurement of the external noise using reference channels is tried. The noise subtraction model is shown in Fig.3. In Fig.3, signal and external noise in the k-th signal channel are represented by s_k and n_k, respectively. The external noise in the reference channel is denoted by n_α and n_β. Uncorrelated additive random noise in these channels are also represented by m_k, m_α, and m_β, respectively. Low pass filter denoted by *H(z)* is applied to the reference channels to remove additive random noise. The additive random noise is assumed to be sufficiently suppressed by the filter and is not further considered in the analysis for simplicity. Using the model shown in Fig.3, the system output is given by

$$\begin{aligned} e_k(t) &= r_k(t) - x_k(t) \\ &= s_k(t) + n_k(t) + m_k(t) - x_k(t) \end{aligned} \qquad (1)$$

where $r_k(t)$ is the measured signal expressed as a sum of true signal $s_k(t)$ plus external noise n_k and random noise m_k. The estimation of external noise using the reference channel data is given by

$$x_k(t) = w_1^k n_\alpha(t) + w_2^k n_\beta(t) \qquad (2)$$

In equation (2), the adaptive filters $W_1(z)$ and $W_2(z)$ are simply assumed to be scales that are adaptively changed. From equation (1), one obtains

$$E[e_k^2] = E[s_k^2] + E[m_k^2] + E[\{n_k - x_k\}^2] \qquad (3)$$

In representing equation (3), all cross terms are assumed independent. The estimation of external noise, $x_k(t)$, may be obtained by minimizing $E[\{n_k - x_k\}^2]$. From equation (3), this condition may be equivalently expressed as minimizing $E[e_k^2(t)]$, since the terms $E[s_k^2(t)]$ and $E[m_k^2(t)]$ have deterministic values [2]. If $e_k(t)$ is an ergodic process, minimizing $E[e_k^2(t)]$ may be achieved by minimizing the power of the system output given by

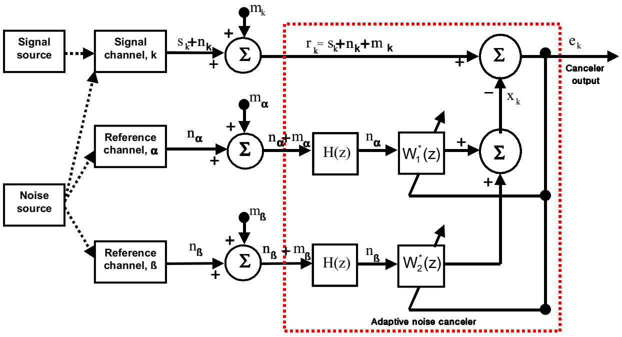


Figure 3: *Adaptive external noise subtraction for MEG signal.*

$$L_k = \sum_t \{r_k(t) - w_1^k n_\alpha(t) - w_2^k n_\beta(t)\}^2 \qquad (4)$$

Thus

$$\frac{\partial L_k}{\partial w_1^k} = \frac{\partial L_k}{\partial w_2^k} = 0 \qquad (5)$$

From equation (5), the scales are obtained by solving the simultaneous equation given by

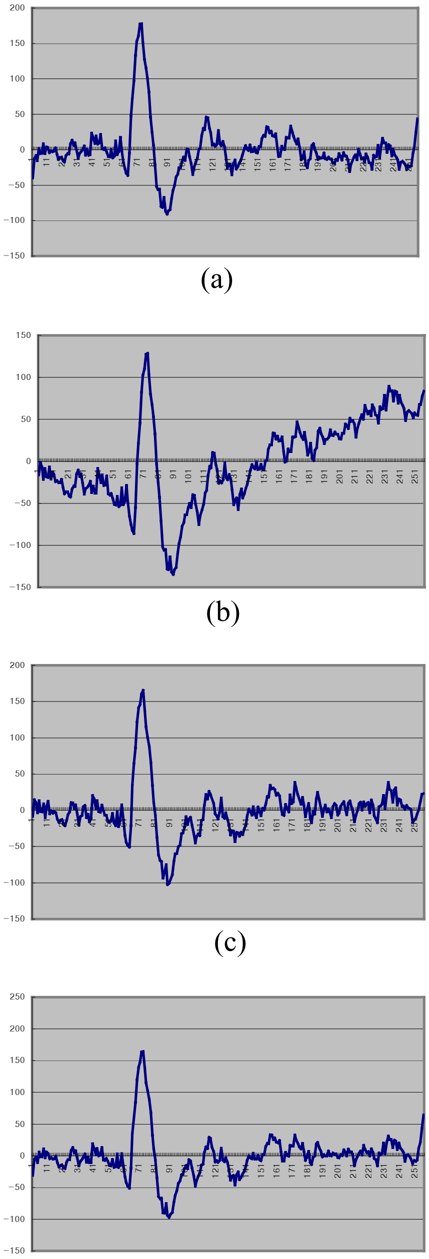
$$\begin{bmatrix} \sum n_\alpha n_\alpha & \sum n_\alpha n_\beta \\ \sum n_\beta n_\alpha & \sum n_\beta n_\beta \end{bmatrix} \begin{bmatrix} w_1^k \\ w_2^k \end{bmatrix} = \begin{bmatrix} \sum r_k n_\alpha \\ \sum r_k n_\beta \end{bmatrix} \qquad (6)$$

3 Results

Auditory evoked field is measured with the noise subtraction model. Performance of the noise subtraction is measured with the system output power given by equation (4). Table 1 shows evaluation of the system output powers for various subtraction models with two data set: one is a set measured without subject or signal, and the other set with a subject measuring auditory evoked field. As previously mentioned, the system output power should be minimum for both the data set with or without neuromagnetic signal. In Table 1, the system output powers are calculated for the cases without noise subtraction (i), noise subtraction with fixed scales (ii), adaptive subtraction without filtering (without *H(z)* in Fig.3) (iii), and the proposed adaptive subtraction as in Fig.3 (iv). The obtained auditory evoked fields corresponding to Table 1(b) are also shown in Fig.4.

Table 1: *The system output powers in the signal measured without subject (a) and with a subject measuring auditory evoked field (b) for various noise subtraction methods.*

Methods	Output powers(a)	Output powers(b)
Without subtraction	173726	47385
Non-adaptive subtraction	55203	20852
Adaptive subtraction without filtering	39353	14630
Adaptive subtraction with filtering	29825	14123



(a)

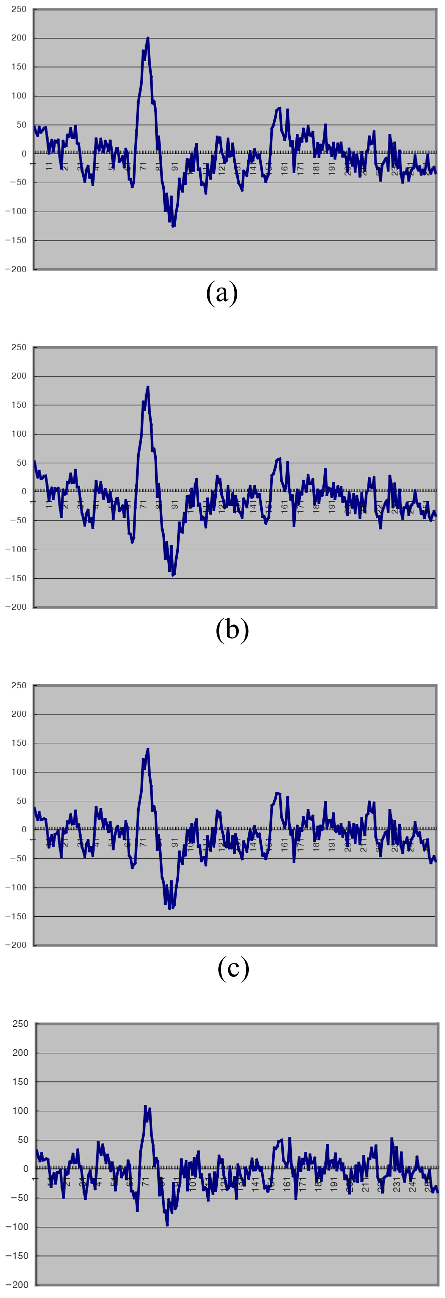
(b)

(c)

(d)

Figure 4: *Auditory evoked fields obtained with various noise subtraction methods: (a) without noise subtraction, (b) noise subtraction with fixed scales, (c) adaptive subtraction without filtering, and (d) adaptive subtraction with filtering.*

In these measurements, sampling rate was 256Hz, and 60 epochs were used. As is seen in the Table 1 and Fig.4, the proposed adaptive noise subtraction method shows the lowest output power and the best performance. Evoked fields obtained with various adaptation periods are shown in Fig.5. As is seen in Fig.5, adaptation periods of 1 or 1/2 epoch show best performances although the variance in equation (4) is monotonically decreasing, as the adaptation period becomes shorter. Topographical mapping of the evoked field is shown in Fig.6 [3]. Due to the limited coverage of the SQUID sensors (10cm x 10cm), signal at the boundary is duplicated before the cubic spline interpolation in the topographic map.



(a)

(b)

(c)

(d)

Figure 5: *Evoked fields obtained with various adaptation periods: (a) 1 epoch, (b) 1/2 epoch, (c) 1/4 epoch, and (d) 1/8 epoch.*

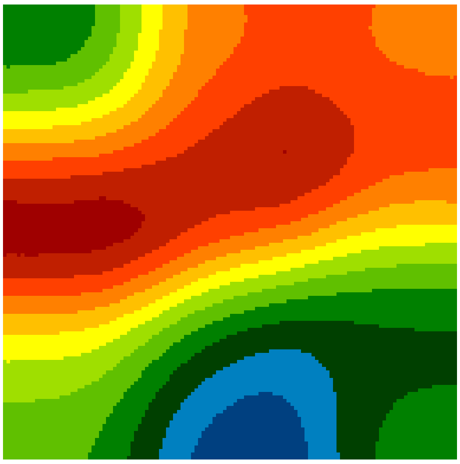


Figure 6: *Topographical mapping of the measured auditory evoked fields with the developed 40 channel MEG system.*

4 Discussion

Adaptive noise subtraction method shows better performance than non-adaptive methods where subtraction scales are fixed over the entire experiments. This is partially due to time-varying and space-varying characters of the noise source. Minimum output power criterion is based on the assumption that signal and estimation error are uncorrelated. Optimal update period of the subtraction scales is about 1 to half epochs for the measurement of evoked field. With these methods, auditory evoked field was successfully measured. Mapping of the measured evoked fields is also tried by the developed 40 channel MEG and signal processing system.

References

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